



# High Field Superconducting Magnets

Fred M. Ašner

*former CERN scientist*

*European Organization for Nuclear Research  
Geneva, Switzerland*

CLARENDON PRESS · OXFORD  
1999

# CONTENTS

The plates fall between pages 172 and 173

<b>NOMENCLATURE</b>	xiii
<b>1 INTRODUCTION AND SUMMARY</b>	1
<b>2 BASIC FEATURES OF SUPERCONDUCTIVITY</b>	5
2.1 Discovery of superconductivity	5
2.2 The two-fluid thermodynamic theory	7
2.3 Skin effect in superconductors	10
2.4 Flux quantization	13
<b>3 FLUX-JUMPING IN SUPERCONDUCTIVE FILAMENTS AND COMPOSITES; STABILITY CRITERIA</b>	20
3.1 Introduction	20
3.2 Stability criteria for superconductive filaments and composites	21
3.2.1 Adiabatic stability	21
3.2.2 Dynamic stability	23
3.2.3 Twistpitch and transposition	28
<b>4 MAGNETIZATION AND AC LOSSES IN SUPER-CONDUCTORS</b>	31
4.1 General remarks	31
4.2 Magnetization losses in superconducting filaments	31
4.3 Resistive losses in superconducting wires and composites	35
4.4 AC losses in flat superconducting cables	38
4.5 Experimental determination of the magnetization coefficients and of the losses	41
<b>5 MANUFACTURING AND APPLICATION OF ADVANCED TECHNICAL SUPERCONDUCTORS</b>	45
5.1 Introduction	45
5.2 Manufacturing of NbTi superconductors	45
5.3 Artificial pinning centre-APC-NbTi superconductors	50
5.4 Intermetallic A15 compound superconductors Nb <sub>3</sub> Sn and V <sub>3</sub> Ga	52
5.5 Manufacturing of fine filamentary Nb <sub>3</sub> Sn composites	53
5.5.1 The bronze process	53
5.5.2 The internal Sn process	56
5.5.3 The modified jelly roll or MJR process	58
5.5.4 The Nb powder method	62

5.5.5	Nb <sub>3</sub> Sn superconductors at temperatures below 2 K and their application to very high fields	63
5.5.6	The critical current dependence upon transverse pressure in Nb <sub>3</sub> Sn strands and cables	63
5.6	Other high field superconductors	65
<b>6</b>	<b>COOLING OF SUPERCONDUCTING HIGH FIELD MAGNETS</b>	<b>71</b>
6.1	General remarks about losses in superconducting magnets	71
6.1.1	Parameters for the heat equations	74
6.2	Pool boiling He I cooling	74
6.2.1	Steady state and transient heat transfer coefficients	74
6.2.2	Heat transfer coefficients for forced flow, two-phase He I	78
6.2.3	Transient heat transfer coefficients	79
6.2.4	Heat equations and stability in pool boiling He I	83
6.2.5	Stability conditions in pool boiling He I cooling with time dependent perturbations	85
6.3	Forced flow cooling with single-phase supercritical helium	88
6.4	Superconducting high field magnets cooled with superfluid He II	92
6.4.1	General remarks	92
6.4.2	Thermodynamic properties of superfluid He II	92
6.4.3	Steady state heat transfer in superfluid helium	94
6.4.4	Heat transport through the insulation of superconducting cables cooled with superfluid He II	101
6.4.5	Cryostats for magnet tests in superfluid He II at 1 bar	104
<b>7</b>	<b>THE QUENCHING PROCESS IN SUPERCONDUCTING MAGNETS AND THEIR PROTECTION</b>	<b>107</b>
7.1	General	107
7.2	Relations determining the quench propagation	108
7.3	External discharge resistor protected and self-protected magnets	111
7.4	Computer codes for quench calculations	112
<b>8</b>	<b>TRANSVERSE BEAM DYNAMICS IN CIRCULAR PARTICLE ACCELERATORS FOR HIGH ENERGY PHYSICS</b>	<b>117</b>
8.1	Introduction	117
8.2	Particle motion in a fixed and curved coordinate system	117
8.3	Accelerator magnets and their transfer matrices	125

<b>9</b>	<b>WINDING CONFIGURATIONS FOR SUPERCONDUCTING ACCELERATOR MAGNETS</b>	<b>132</b>
9.1	Introduction	132
9.2	Magnetic field calculations ...	133
9.3	End field calculations	142
9.4	Field harmonics due to magnetization currents...	146
9.5	Field errors due to manufacturing and assembly tolerances	149
9.6	Computer codes for magnetic field computations	151
<b>10</b>	<b>MECHANICAL COMPUTATIONS AND DESIGN PRINCIPLES FOR SUPERCONDUCTING MAGNETS</b>	<b>155</b>
10.1	Introduction	155
10.2	Forces, stresses, and strains in superconducting magnets	155
10.3	Mechanical design principles	162
10.4	Final magnet design and the manufacturing aspects	173
10.5	Future prospects for very high field superconducting ...	179
<b>11</b>	<b>COOLING OF LARGE ACCELERATOR MAGNET SYSTEMS</b>	<b>183</b>
11.1	Heat loads in large accelerator magnet systems	183
11.2	Cooling systems	183
<b>12</b>	<b>HIGH FIELD SOLENOIDS AND DETECTOR MAGNETS</b>	<b>192</b>
12.1	Introduction	192
12.2	Computation of magnetic fields in solenoids	192
12.3	Calculation of mechanical forces and stresses in solenoids	196
12.4	Basic principles of nuclear magnetic resonance	199
12.5	Design and manufacture of high field NMR solenoids	200
12.6	Large superconducting solenoids and toroids	202
<b>13</b>	<b>MAGNETIC MEASUREMENTS OF SUPERCONDUCTING MAGNETS</b>	<b>209</b>
13.1	Introduction	209
13.2	The main magnetic field measuring methods	209
13.2.1	The rotating or harmonic coil	210
13.2.2	Field measurements with Hall probes	214
	<b>References</b>	<b>218</b>
	<b>Index</b>	<b>231</b>